

# An evidence for indirect detection of dark matter from galaxy clusters in Fermi-LAT data

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We search for spectral features in Fermi-LAT gamma-rays coming from regions corresponding to six most massive nearby galaxy clusters. We observe a sharp peak at photon energy 130 GeV over the diffuse power-law background with statistical significance up to  $3.2\sigma$ , confirming independently earlier claims of the 130 GeV gamma-ray line from the Galactic centre. Interpreting this result as a signal of dark matter annihilations to monochromatic photons in galaxy cluster haloes, and fixing the annihilation cross section from Galactic centre data, we determine the annihilation boost factor due to dark matter subhaloes to be of order  $\mathcal{O}(10^3)$ , in agreement with theoretical expectations for the galaxy clusters.

## I. INTRODUCTION

After the discovery of Higgs boson at CERN, the most important unsolved question related to the origin of mass of the Universe is what is the cold dark matter (DM). Firm evidence for the DM existence is coming from various gravitational effects in astrophysics and cosmology [1]. Unfortunately the direct [2] and indirect [3] searches for DM particles have all given either negative or contradictory results.

A notable exception to this result is the recent evidence for monochromatic gamma-ray line with energy 130 GeV [4–7] in the Fermi Large Area Telescope (LAT) [8] data. This signal originates predominately from a small region in the Galactic centre and is spatially not associated with astrophysical objects such as the Fermi bubbles [6, 7]. It is consistent with the Fermi-LAT bound on monochromatic photon lines from diffuse gamma-ray data [9]. High global statistical significance of the signal between  $4.5\sigma$  and  $6.5\sigma$ , depending on the details of different studies, makes the possibility [10] that it is a statistical fluctuation very unlikely. Ignoring the option that the 130 GeV gamma-ray line is a fake detector effect, Fermi-LAT has either observed some astrophysical process that unexpectedly gives a photon peak [11, 12] or detected the DM annihilations or decays [13–33] to monochromatic photons.

To verify that the DM has been observed indirectly, the Fermi-LAT signal must either be confirmed by other experiments such as the planned high-resolution experiments CALET [34] or TANSUO [35], or to observe the same peak in photons coming from other known DM dominated objects in addition to the Galactic centre. The expected signal from nearby dwarf galaxies turned out to be too weak to check the 130 GeV gamma-ray line with Fermi-LAT [36]. However, the galaxy clusters, the biggest nearby cosmological structures dominated by DM, are expected to be much better objects for that purposes [37–40] because the DM annihilation signal from there should be amplified by a large boost factor due to the existence of many DM subhaloes [41–46].

The aim of this work is to search for spectral features in the gamma-ray spectrum originating from the known galaxy clusters in Fermi-LAT data. We work with the six biggest nearby clusters collected in Table I. Because of limited Fermi-LAT statistics and because of uncertainties related to the sizes/masses of the dark matter haloes of galaxy clusters we treat all the galaxy clusters as equally important and sum up all the photons coming from the direction of these clusters. To do that we vary radii of the chosen sky areas in the direction of galaxy clusters in order to study from which areas the expected signal comes from.

We observe a peak-like excess with photon energy 130 GeV *exactly* as in the case of the Galactic centre. Maximal significance of the signal,  $3.2\sigma$ , is obtained for galaxy cluster radius 4 degrees that agrees well with the estimated sizes of the galaxy clusters. We fix the DM annihilation cross section from Galactic centre data and compute the boost factor that turns out to be between 1800 and 3800, in agreement with theoretical estimates. Our results strongly support the claim that Fermi-LAT has indirectly detected DM annihilations to monochromatic photons. It is unlikely that the signal from spatially unrelated sky regions (the centre of Galaxy and the positions of galaxy clusters) with exactly the same shape and energy is due to statistical fluctuation. Since astrophysics in the Galactic centre should be very different from astrophysics in large galaxy clusters, astrophysical explanation to the observed line is also disfavoured. Our results exclude the possibility that DM decays are responsible for the 130 GeV gamma-ray line, large boost factor implies DM annihilations in small subhaloes. This result has important implications for theoretical DM model building as well as for cosmology of DM haloes.

## II. DATA ANALYSES

### A. Selection of galaxy clusters

We select six galaxy clusters presented in Table I. The selection is motivated by earlier studies, e.g. [43, 47, 48]. The selection criteria is the strongest annihilation signal of DM restricting us to nearby and massive galaxy clusters. While both mass and distance have systematic errors and boost factor can be different in various clusters due to the different formation history for galaxy clusters, it allows to pile up the observed  $\gamma$ -ray photons from the selected cluster regions with same statistical weights. Due to the limited statistic in Fermi LAT data, we cannot study clusters individually, and using same statistical weights for all clusters does not influence our detected signal. It only slightly influences the derived boost factor, which is very poorly constrained from our study.

### B. Data selection and point sources

In the present analysis, we consider the public Fermi LAT photon event data of 206 weeks (from 4 Aug 2008 to 8 July 2012) within energy region from 20 to 300 GeV [8]. We apply the zenith-angle cut  $\theta < 100^\circ$  in order to avoid contamination with the earth albedo, as recommended by the Fermi LAT team. We also apply the recommended quality-filter cut DATA\_QUAL= 1, LAT\_CONFIG= 1, and ABS(ROCK\_ANGLE)< 52. We make use of the ULTRACLEAN events selection (Pass 7 Version 6), in order to minimize potential systematical errors. The selection of events as well as the calculation of exposure maps is performed using the 18 April 2012 version of ScienceTools v9r27p1.

To avoid the effect of point sources we exclude photons that are within an energy-independent cut radius of each source. We used all (1873) sources from the LAT 24 month catalog [49]. The cut radius is considered  $0.2^\circ$  [9]. In addition, we tested the radii  $0.15^\circ$ ,  $0.25^\circ$  and  $0.5^\circ$  resulting no significant effect on final results.

To estimate the photon spectrum related to the clusters we select photons that are within an energy independent radius around the centre of the clusters. In the present analysis we use radii  $R = 1, 2, \dots, 10$  and  $15$  degree. We expect the annihilation signal arises mainly from the region 2-3 degrees assuming the boost factor due to substructures of DM and the signal is rather flat (e.g. [43]). The morphology of the signal of the main halo is different. It arises from small region  $R < 0.2^\circ$  and has very cuspy nature (e.g. [48]). Having a reasonable model of substructure the total flux due to substructure is many orders of magnitude larger than the total flux of main halo in the region  $R > 0.2^\circ$  [43]. Due to the limited statistics we cannot study smaller regions than  $R = 1-2^\circ$ .

### C. Spectral estimation

To estimate the  $\gamma$ -spectrum we sum up all photons from the selected cluster regions. Table II presents the total number of photons. The spectrum is calculated by the kernel smoothing described in detail elsewhere [6]. For comparison, we calculate spectrum in logarithmic and linear energy scale however, the results remain same. Figure 1 shows the estimated spectrum for a set of radii  $R$  and the theoretical power-law background with the spectral index 2.6.

## III. RESULTS

### A. Estimation of peak significance

We use Monte Carlo (MC) method to estimate the significance of the spectral features. We select six random cluster-size regions on sky and then we use the above described method to estimate the  $\gamma$ -spectrum. To avoid the crowded region at the Galactic plane and centre of the Galaxy we exclude the region  $|b| < 5^\circ$  from the study [9]. It means the border of a randomly selected region can not be closer to the Galactic plane than  $|b| = 5$ . We tested different sizes of the excluded regions:  $|b| < 5$ , 10 and 15 degrees having neglectable effect on results.

For significance estimation of the spectral features we repeat the procedure 10,000 times for all the selected cases of radii to get the distribution of spectra. Based on 10,000 Monte Carlo realizations we estimated the confidence limits (CL) of the spectra. Figure 1 shows 99.7% CL denoted with the blue band. Table II gives the numerical results. We see that the significance rises up to 3–4 degree for cluster radius and then remains approximately constant in range  $\sim 3.1\sigma$ . It shows that the signal arises from 3 to 4 degrees from the cluster centre (roughly the radius of the cluster) and using larger radii it only increase the number of background photons. If the radius is larger than 10 to 15 degrees, the number of signal photons compared with the background photons is too low and the observed peak is strongly affected by the background fluctuations.

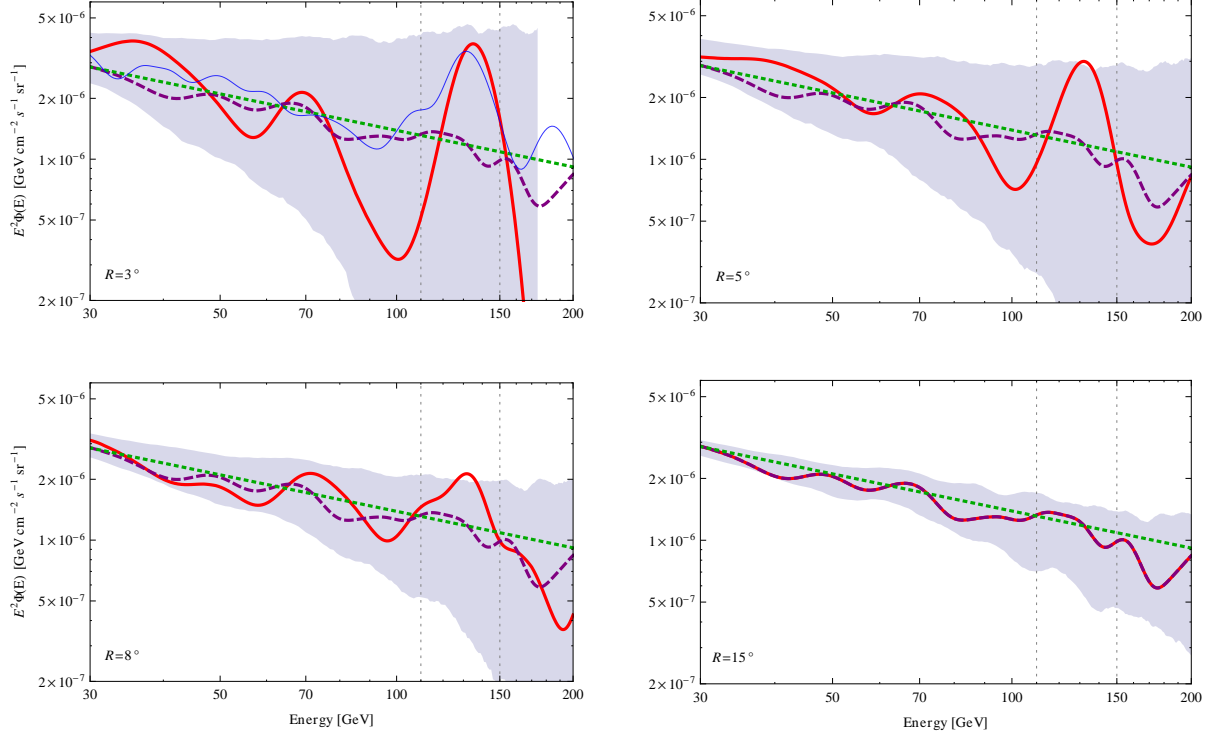


FIG. 1: Calculated  $\gamma$ -ray spectrum originating from the selected region around the clusters (red solid curve).  $R$  denotes the radius of the selected regions. The gray band shows 99.7% CL from the Monte Carlo analyses. The green dotted curve shows the ideal power-law background with the spectral index 2.6 and the purple dashed curve is the spectrum of the 15-degrees wide region around the clusters. The blue solid line in upper left panel shows the 17 times reduced signal from Galactic centre for comparison.

### B. Estimation of the boost factor

Figure 1 and Table II presents the evidence of the peak in the energy region 110...150 GeV with the maximum around 130 GeV. The small number of events makes estimation of exact morphology of the signal impossible. Assuming the signal comes from DM annihilation, we can estimate the boost factor due to substructures of the main DM halo of the cluster. The relation between the number of signal photons  $N_{\text{signal}}$  within solid angle  $\Delta\Omega$ , the properties of DM particle and the boost factor  $B$  is given by

$$\frac{N_{\text{signal}}}{T_{\text{exp}}} = \frac{1}{4\pi} \frac{\langle\sigma_A v\rangle}{2m_{\text{DM}}^2} B J_{\Delta\Omega} N_{\text{prod}}, \quad (1)$$

where  $T_{\text{exp}}$  is the exposure time of cluster region  $\Delta\Omega$ ,  $\langle\sigma_A v\rangle$  is the averaged cross-section,  $m_{\text{DM}}$  is the mass of DM particle and  $N_{\text{prod}}$  is the number of produced photons per annihilation (in case of non-self-conjugated particle there is addition factor two in front of  $m_{\text{DM}}$ ). The  $J$ -factor  $J_{\Delta\Omega}$  is defined by the line-of-sight (l.o.s) integral

$$J_{\Delta\Omega} = \int_{\Delta\Omega} d\Omega J(\Omega) = \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} ds \rho^2(s, \Omega), \quad (2)$$

where  $\rho(s, \Omega)$  is the density profile of DM in galaxy cluster. The parameters of the main DM halo is considered from [48].

We assume the annihilation cross-section is  $0.1 \times \langle \sigma_A v \rangle_{\text{th}}$ , where  $\langle \sigma_A v \rangle_{\text{th}} = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  is the standard thermal cross-section, motivated by the  $\gamma$ -ray line signal from the Galactic centre [5, 6]. Considering the radius  $R = 4^\circ$ , the boost factor of substructure is  $1800 \dots 3800$ , where the variation is estimated 68% CL using bootstrap analysis. The number is very reasonable (e.g. see discussions and references in [43]), the large error is because of low number of photons. We remind the other sources of error are not estimated here, the distance and mass of clusters, averaging over the selected clusters, the error of the mass of DM particle, the main DM profile of the clusters etc. In addition, the value of  $0.1 \times \langle \sigma_A v \rangle_{\text{th}}$  itself depends on uncertainties of the Galactic DM halo. Taking into account all these errors, the resulting boost factor can be a magnitude larger or smaller than presented here.

#### IV. CONCLUDING REMARKS

We have found an excess of high energy gamma-rays originating from six nearby galaxy clusters in Fermi-LAT publicly available data. The excess with global statistical significance  $3.2\sigma$  has a form of sharp peak with photon energy 130 GeV. We find that the signal originates from  $\mathcal{O}(4^\circ)$  areas associated with the galaxy clusters, in agreement with the estimated size of those. Our result provides an *independent* confirmation of the previously claimed 130 GeV photon line from the Galactic centre and strongly supports the interpretation of the result due to DM annihilations to monochromatic photons. Fixing the DM annihilation cross section from the Galactic centre data, we find that the boost factor for DM annihilations due to DM substructures in the galaxy cluster haloes is in a good agreement with theoretical expectations. In fact the large boost factor is the reason why the signal is detectable with Fermi-LAT. Therefore our result excludes DM decays as an explanation to the 130 GeV gamma-ray line.

The galaxy clusters, as well as the Galactic centre, are fixed objects dominated by DM, thus our result does not suffer from statistical fluctuations related to scanning and choosing arbitrary regions of the sky nor from possible astrophysical effects from the Galactic disc. The fact that the peak is *exactly* at 130 GeV in unrelated regions of sky, in the Galactic centre and in the locations of galaxy clusters, strongly suggests that this is not statistical fluctuation. Also astrophysical explanation to the gamma-ray line is now disfavoured since astrophysical processes should not be exactly the same in galaxy clusters and in the Galactic centre. Our result implies that, perhaps, DM of the Universe has been discovered via indirect detection by Fermi-LAT.

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TABLE I: The selected galaxy clusters. Galactic coordinates, observed redshifts and luminosity distances (corrected relative to the motion in respect of the cosmic microwave background (CMB)) are taken from the NASA/IPAC Extragalactic Database (<http://nedwww.ipac.caltech.edu/>). The virial mass of Fornax, M49, NGC4636 and Centaurus clusters are derived from [50], while the mass of Virgo is derived from [45] and mass of AWM7 from [51]. For masses and luminosity distances we assume the following cosmology: the Hubble constant  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , the matter density  $\Omega_m = 0.27$  and the dark energy density  $\Omega_\Lambda = 0.73$  [52].

Cluster	$l$ (deg)	$b$ (deg)	Redshift	$M_{\text{vir}}$ ( $10^{14} M_\odot$ )	$D_{\text{lum}}$ (Mpc)
AWM7	146.35	-15.62	0.0172	6.08	69.2
Fornax	236.72	-53.63	0.0046	1.65	17.7
M49	286.92	70.20	0.0044	0.85	22.7
NGC4636	297.74	65.48	0.0032	0.23	17.9
Centaurus	302.41	21.56	0.0114	4.49	51.2
Virgo	279.68	74.46	0.0036	6.9	19.4

TABLE II: The number of  $\gamma$ -ray events, the 130 GeV peak signal events and the significance of the signal estimated from MC analysis. Note that the number of signal photons is calculated assuming a monochromatic 130 GeV peak and due to the low number of observed photons in this peak region, the error are factor of two. However, it does not affect the significance of observed peak since this is calculated from MC analysis.

<b>Radius <math>R</math> (deg)</b>	1	2	3	4	5	6	7	8	9	10	15
$N$ (110...150 GeV)	2	4	6	10	16	24	30	35	40	48	101
$N$ (20...300 GeV)	15	55	114	219	336	504	666	875	1105	1370	3044
$N_{\text{signal}}$ (110...150 GeV)	1.6	2.2	2.0	3.2	4.5	5.6	7.2	9.5	8.8	7.4	4.6
Significance ( $\sigma$ )	2.0	2.7	2.7	3.2	3.2	3.1	3.1	3.0	3.0	3.0	2.9

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